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A technique for tropospheric communication performance estimation

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Abstract In this paper a technique considered to be the best suitable under Indian varied meteorological condition is provided for the prediction of transmission loss for all modes of tropospheric radiowave propagation. Such estimation can be made for clear air, precipitation and water vapour (gaseous) molecules. Some of the methods presented in this paper, have been developed on the basis of the radio propagation measurements carried out over different locations in India and the exhaustive work done on radioclimatology over the Indian subcontinent. The effects of various meteorological parameters on radiowave propagating through the troposphere have been tested before developing this technique. The technique is applicable for both terrestrial and earth space paths.

Keywords Tropospheric communication circuit, line of sight diffraction, transhorizon field strength

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1. Introduction

The estimation performance of communication links in VHF, UHF, microwave and millimetrewave frequency bands is done by different prediction techniques. Such prediction models are usually emperical formulae derived from experimental links measurements. Some models are also derived even by taking the propagation phenomena into consideration. The propagation phenomena are different for different modes of propagation and frequencies. The most important requirement of such models is the input parameters including terrain profiles, system characteristics and meteorological conditions.

An exhaustive work has been carried out in relation to both radio propagation factors and radio climatological parameters over India. It is found that the propagation conditions are different over different geographical regions. In clear air condition, it is seen that the transhorizon propagation condition is found to be good over the Indian coastal stations where the superrefraction conditions prevail for significant percentage of time in a year while over the northern plains where the summer and winter are well defined, the propagation condition is normal. The propagation situation over Indian arid region and some parts of Gujarat is seen to be substandard while over the southern and central plains, the transhorizon propagation condition is seen to be normal. The propagation condition is indifferent over the north-east region of India which consists of a lot of vegetation and hills and the propagation situation over Srinagar region is very different than other parts of the country.

A detailed work has also been carried out towards the characterization of rain rates and water vapour distributions over India. Such results on water vapour and rain rates are the important input parameters in deducing the results on attenuation of radiowave due to rain and water vapour.

In this paper, the most suitable methods for prediction of transmission loss/field strength/attenuation for different modes of propagation *viz.*, line-of-sight (LOS), knife edge diffraction, and troposcatter under clear air conditions have been discussed. The most suitable methods to estimate attenuation over earth space and terrestrial paths have also been presented. A

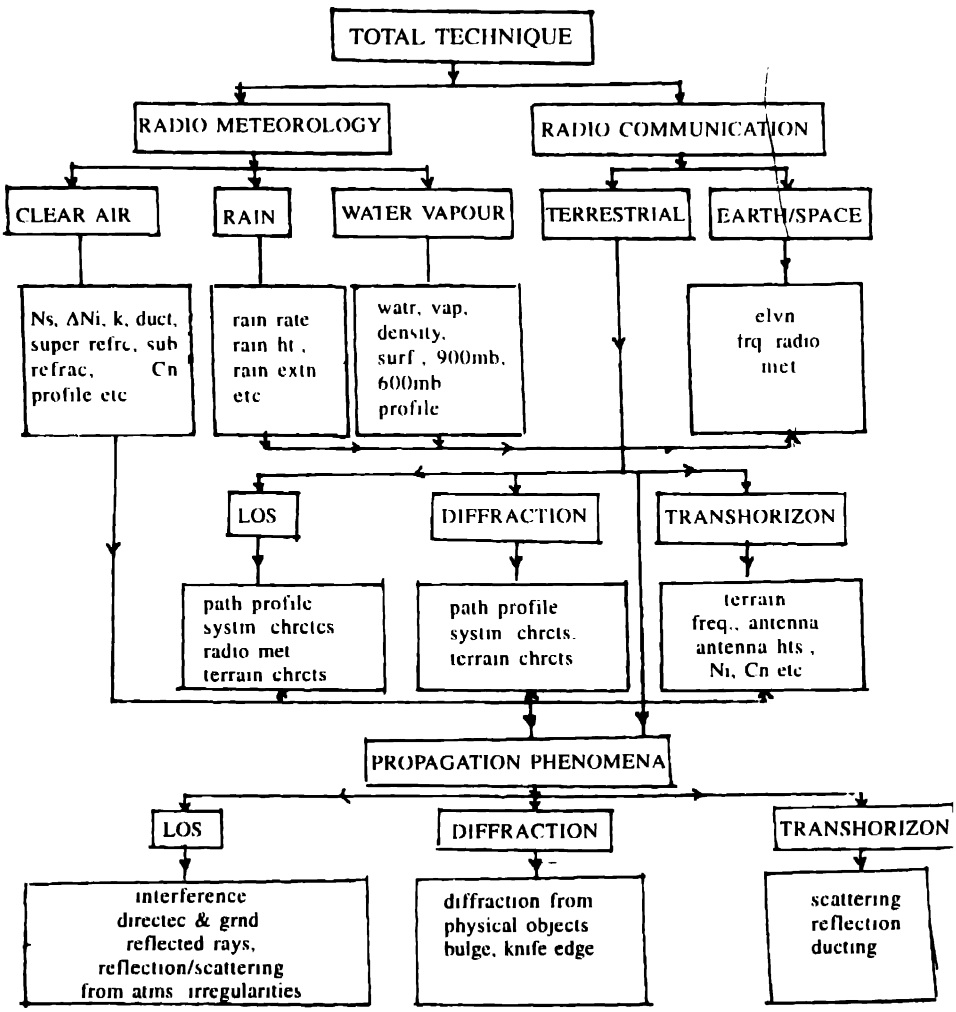

Figure 1. A complete technique for estimation performance of tropospheric communication circuits for different modes of propagation

method for predicting the attenuation due to water vapour gaseous molecules at higher frequencies over earth space path has also been discussed. The technique (structure) for estimation performance under different propagation modes of tropospheric communication systems is presented in Figure 1.

2. Radioclimatology over India

The quality and reliability of tropospheric communication and radar propagation are controlled by radio refractivity profile. An *a priori* knowledge of the radioclimatological parameters in the form of monthly average is a prerequisite for designing LOS and troposcatter systems. From the exhaustive analysis of data pertaining to the period (1968-79) from 32 radiosonde stations and Monex-79 data obtained from the India Meteorological Department, a detailed map of the structure of the vertical gradient of refractivity in the lower surface based layers, effective earth's radius factor, superrefraction and ducting occurrence probability, occurrence characteristics of superrefraction at higher levels and morphology has emerged [1]. It is observed that the annual mean initial refractivity gradient (surface to 250m) which controls the bending of the radiowave is large during all 12 months along the west coast, followed by south-west coast. The gradient values over northern plains are quite high (90-75 N/km) while over central plains the gradient values are rather low during all 12 months The gradient values are moderate over southern plains. The evening hour gradients are less intense than morning hours. The highest gradient values are usually observed during premonsoon months while it is quite low during monsoon The surface duct occurrence probability in the premonsoon period is about 30% over the coastal regions and decreases rapidly towards the central part of the country. Incidence of ducting is the maximum during the premonsoon and is low during the post-monsoon It is higher by a factor of 2 to 3 in the morning than in the evening. The structure intensity parameter C_n^2 has also been determined from radiosonde data and microwave link measurements. The results on C_n^2 are needed to estimate the scattered power of troposcatter link. All such results on radioclimatological parameters can be used directly in the methods for predicting the field strength presented in the following sections

3. Rain rate and water vapour concentration

The rain rate, 0° C isotherm height and water vapour content play a dominant role in terrestrial and earth space communication systems when the frequencies of operation are more than ~ 10 GHz. There was dearth of results on these parameters over the Indian subcontinent. However, the work carried out in recent years have yielded a detailed morphology of the aforesaid parameters over the Indian subcontinent to meet the expanding requirements of the present day radar and communication systems in India. In order to derive rain rate statistics, a chain of rapid response rain gauges (~ 10 sec integration time) were utilised over different locations in India [2]. The recordings of rain rate indicate many features similar to those encountered in amplitude variations of microwave radiowaves. An exhaustive analysis of rain data indicates that the probability percentage of rain rate is maximum over high altitude stations followed by the Indian coast. The rainfall activity is minimum over desert of India, while it is significant over northern plains compared to the other plains of the country. The highest rain intensities occur during monsoon over most of the stations in India. During winter, appreciable rainfall intensities are noticed in many parts of India. An important character is the large variability of rainfall rates due to different topographical features. The rain height in relation to 0° C isotherm height has been estimated recently over different Indian tropical latitudes [3,4]. It is seen that the 0° C isotherm height in monsoon varies from 4.4 km to 6.3 km. There is considerable variation in 0°C isotherm height during the winter months while it varies from 3.66 km to 6.04 km in summer months over different regions of the country. The results on water vapour density derived from analysis of observations [5] over India, exhibit certain clear geographical and seasonal trends. The water vapour density is generally high during monsoon and post-monsoon periods, while the values are of moderate order during summer and winter months. An important character over India is the large diurnal variability in the refractivity profiles caused solely by dominance of high water vapour density. The results on rain rate and rain height are the most important required parameters for deducing attenuation results over earth space path. Such results can be readily used in the prediction technique. Similar is the case with the results on water vapour distribution over India. These results too can be readily used in the method discussed for deducing the results on attenuation of the radiowave due to water vapour over earth space paths in microwave and millimetrewave bands.

4. Line of sight propagation

In line of sight propagation mode, the transmitting and the receiving aerials are within the radio horizon. The radio horizon distance (d_0), is given as

$$d_0 = \sqrt{2a'}\left(\sqrt{h_1} + \sqrt{h_2}\right),$$

where

a' is the effective earth's radius,

h_1 is the height of the transmitting antenna,

and h_2 is the height of the receiving antenna.

The effective earth's radius is expressed as

$$a' = ka,$$

where k is the effective earth's radius factor and a is the radius of the earth.

The effective earth radius depends on the initial refractivity gradient (ΔN_i) and is expressed as

$$k = \frac{1}{1 + a \cdot \Delta N_i \times 10^{-6}}$$

The radio horizon for standard atmosphere (ΔN_i -- 40 N/$_{\mathrm{km}}$) and ($k = 4/3$) is approximated as

$$d_0 = 3.84\left(\sqrt{h_1} + \sqrt{h_2}\right).$$

Line of sight range mainly depends on the heights of the transmitting and receiving antennas and initial refractivity gradient. The line of sight range is extended if the initial refractivity gradient is more.

In case of line of sight propagation, the received signal is a combination of direct ray and ground reflection with a possible contribution from scattering, layer reflection *etc*. The attenuation depends on antenna characteristics, radiometeorology and terrain features. The attenuation is estimated on the geometric optics model for direct ray (E_1) and the reflected ray from the ground (E_2). The resultant field is expressed as

$$E = E_1 + E_2,$$

where E_1 is the instantaneous field due to the direct ray and is given as

$$E_1 = \frac{245\sqrt{P_1 G_1}}{r} e^{i\omega t}$$

and E_2 is the instantaneous field due to the ground reflected ray and is given as

$$E_2 = \frac{R \cdot 245\sqrt{P_1 G_1}}{r + \Delta r} e^{i(\omega t - \theta - 2\pi/\lambda)\Delta r}$$

where P_1 is the transmitted power G_1 is the gain of the transmitting aerial. G_2 is the gain of the receiving aerial. λ is the wavelength, R is the reflection coefficient, r is the propagation factor and Δr is the path length difference.

The reflected ray differs from the direct one both in amplitude and phase. The difference in amplitude is caused by the inevitable losses of energy due to reflection. The difference in phase is due to the phase shift in reflection and retardation in phase in path length. The path length difference (Δr) of the direct ray and reflected ray from the ground is estimated by using

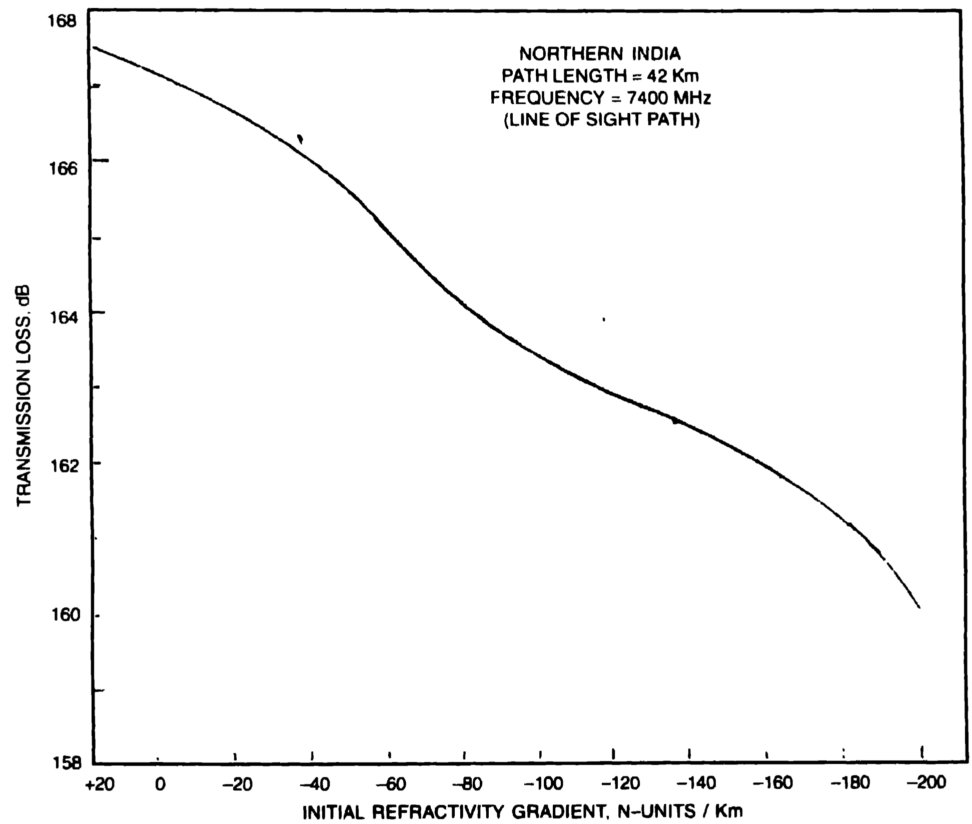

Figure 2. Field strength variation for line of sight propagation.

ray tracing programme. The reflection coefficient is a function of the conductivity (σ), dielectric constant (ε) and terrain roughness factor (Δh). In all practical cases, $\Delta r << r$ so that Δr may be neglected in comparison with r in the denominator of the equation for the estimation of instantaneous field due to the ground reflected ray. However, under no circumstances Δr is neglected in the exponent.

In view of this, the rms value of E can be expressed in terms of attenuation F and expressed as

$$F = \sqrt{1 + 2R\cos\left(\theta + \frac{2\pi}{\lambda}\cdot \Delta r\right) + R^2}\ .$$

The field due to layer reflection (E) is estimated by the following expression

$$E_3 = E_0 \cdot (\Delta n)^2 / 4\phi^4 \left(1 + \left(\frac{\pi\, b\phi}{\lambda}\right)^2\right)^2 ,$$

where E_0 is the received field in free space condition, ϕ is the grazing angle, b is the thickness of the layer and Δn is the change in refractive index through the layer. The resultant field. E is expressed as

$$E = E_1 + E_2 + E_3\ .$$

The estimated transmission loss over a line of sight path situated in Northern India having path length ~ 42 km and 7.6 GHz is illustrated in Figure 2.

5. Knife-edge-diffraction

A propagation path with a common horizon for both terminals may be considered as having a single diffracting knife edge. The common horizon may be a mountain ridge or similar obstacle and such paths, sometimes are referred to as obstacle gain paths. In some cases, over relatively smooth terrain or over the sea, the common horizon may be the buldge of the earth rather than an isolated ridge. This case is not covered under knife-edge diffraction.

In a diffraction path, one also finds two knife edges, such path is termed as double knife edge diffraction. In double knife edge path, the first path consists of transmitter, first ridge and second ridge. The second path is a combination of first ridge, second ridge and receiver. The attenuation A (v) due to diffraction is computed for each of the two paths and the sum of the attenuation gives the resultant attenuation over the paths.

In order to estimate the angular distance (θ), one first determines the angles (θ_{et} and θ_{er}) by which the horizon rays are elevated or depressed to the horizontal at each antenna

$$\theta = \theta_{et} + \theta_{er} + \frac{d}{a'}\ .$$

where a' is the effective earth's radius in km and a' is estimated from the observed initial refractivity gradient (ΔN_i) and d is the path length in km and θ_{et} and θ_{et} are defined as

$$\theta_{et} = \frac{h_{lt} - h_{ts}}{d_{lt}} - \frac{d_{lt}}{2a'}\ .$$

and $$\theta_{er} = \frac{h_{lr} - h_{rs}}{d_{lt}} \qquad \frac{d_{lr}}{2a'}$$

where h_{lt} and h_{lr} are the heights of the obstacles from the above mean sea level. h_{ls} and h_{rs} are the heights of the antennas above the mean sea level d_{lt} and d_{lt} are the horizon distances from the transmitting and receiving terminals.

The values of the above parameters are to be read from the terrain profile. After obtaining the diffraction angle, the loss due to diffraction is estimated. The diffraction loss due to first edge is given as

$$A(v_1) = 12.953 + 20 \log v_1 \text{ (dB)},$$

with v_1 given as

$$v_1 = \pm 2.583\,\theta \sqrt{\frac{fd_{11}d_{21}}{d_1}},$$

where, f is the propagating radiowave frequency, d_{11} and d_{21} are the distances to be read from the terrain profile and d_1 is the total distance in km.

The diffraction loss in dB due to second knife edge is

$$A(v_2) = 12.953 + 20 \log v_2 \text{ (dB)},$$

where $$v_2 = \pm 2.583\,\theta \sqrt{\frac{fd_{12}d_{22}}{d_2}}.$$

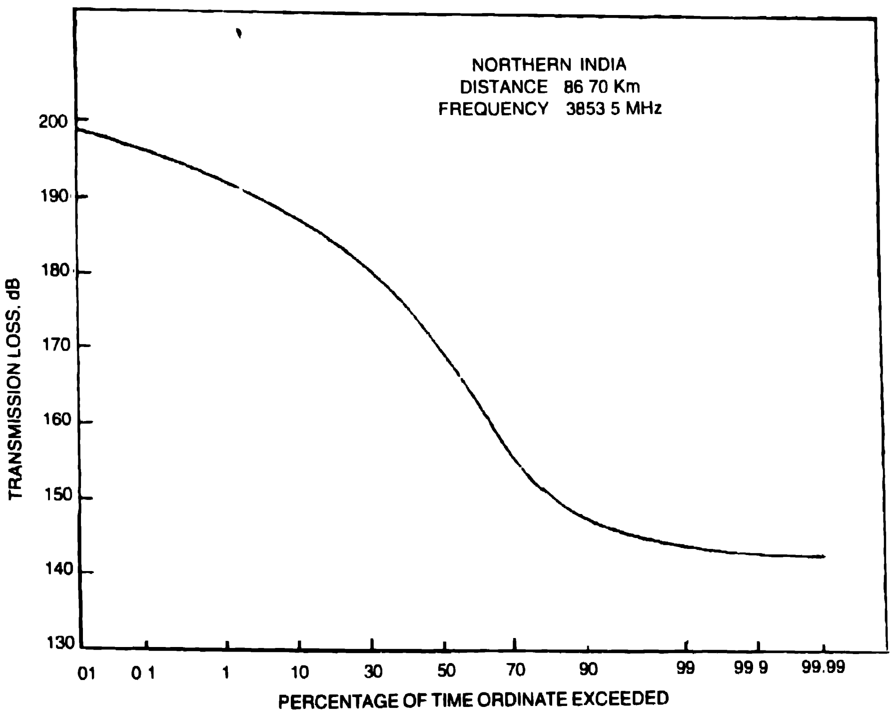

Figure 3. Distribution of transmission loss for double knife diffraction path

and d_{12} and d_{22} are the distances to be read from the terrain profile and d_2 is the total distance in km.

The total knife edge diffraction loss is given as

$$A(v) = A(v_1) + A(v_2).$$

The total loss is the sum of the loss in free space ($L_{bf} = 32.46 + 20 \log d_{km} + 20 \log f_{MHz}$) and diffraction loss ; where L_{bf} is the basic free space loss in dB, f is the frequency in MHz and d is the distance in km.

The transmission loss estimated for the double knife edge diffraction path is presented in Figure 3.

6. Troposcatter propagation

It is wellknown now that in transhorizon propagation, turbulent scattering (homogeneous, isotropic scattering obeying –5/3 spectral law) and reflection due to large number of reflection facets, occur simultaneously. The facets caused by either thermal convection or reduced vertical exchange due to stability, are characterized by high refractivity gradients across the boundaries of these facets and are typically 3 m in thickness with a radius of curvature of the order 1 km. A relationship is assumed between the change of refractive index, Δn through sharp boundaries and spectral intensity C_n^2, of refractive index fluctuations, because the strong gradients are broken through the action of turbulence into spectrum of fluctuations obeying – 5/3 spectral law. This relationship is expressed as

$$\Delta n = 0.6.\ C_n^2\ .\ 10^{10}.$$

The received power due to many facets is given by

$$\frac{P_d}{P_{FS}} = \frac{4}{\pi d^2} \int_V N\ A_e\ dv,$$

where P_d is the power received due to reflection. P_{FS} is the power due to free space propagation. d is the path length, N is the number of facets per unit volume and A_e is the bistatic radar reflection area of facets.

The resultant field strength due to both scattering and reflection due to facets is given by the relation

$$A = \left(\frac{P_S}{P_{FS}} + \frac{P_d}{P_{FS}} \right)$$

where $\frac{P_S}{P_{FS}}$ is the power received due to scattering and is given by the relation

$$\frac{P_S}{P_{FS}} = 0.76 \times 10^{28} \cdot C_n^2 \left(\frac{dM}{dh} \right)^{-14/3} \cdot d^{-11/3} \cdot \lambda^{-1/3} \cdot \alpha^3$$

where dM/dh is the modulus of refractivity, d is the path length and α is the antenna beam width.

The estimated field strength at 4.6 GHz over a trans-horizon path having path length 160 km situated over Indian desert is illustrated in Figure 4.

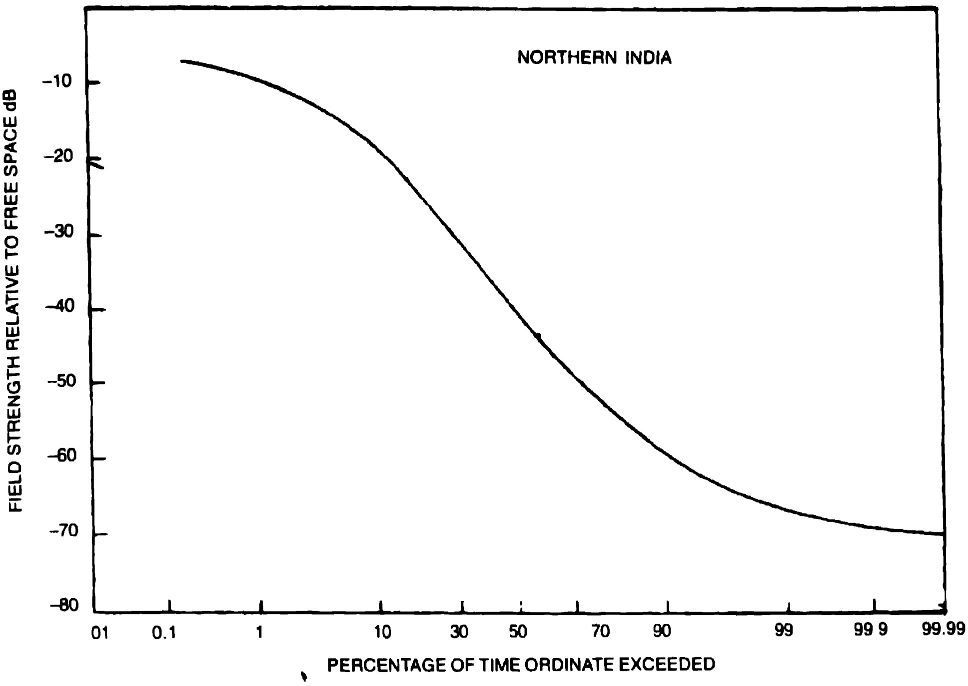

Figure 4. Distribution of field strength for transhorizon (troposcatter) path

7. Rain attenuation over earth space path

The frequency range from 1 GHz to 10 GHz is in use at present by various agencies including both civilian and defence for tropospheric communication circuits in both terrestrial and earth space communication systems in India. The use of higher frequency bands for communication systems is necessary for higher channel capacities and also due to congestions in VHF and UHF bands. The higher frequency (radiowave) especially when the frequency of operation is more than ~ 10 GHz is affected severely by rain and other hydrometeors. Rain is the most important one and it attenuates the radiowave severely.

The characteristics of microstructure of rainfall including size distribution, temperature, terminal velocity and shapes of rain drops are very important for the determination of specific attenuation at a particular frequency for different rain rates. The relation between the specific attenuation α and rain rate R for practical purposes is given by the following well known power law [6].

$$\alpha = a R^b,$$

where a and b are the constants depending on the frequency.

The values of a and b have been estimated by assuming the rain drops to be oblate spheroidal [7, 8] and is presented in Table 1. The specific attenuations can be deduced for different measured rain rate at various frequencies ranging between 1 GHz and 400 GHz. The non-uniformity of rainfall in horizontal and vertical directions makes the evaluation of attenuation along earth space path complex. The model for the slant path suggests that the rain rate (R) exceeded for P% of time at ground level occurs for the same percentage of time upto the height (h_R), called rain height [9, 10]. It is also assumed that the attenuation due to rain does not occur above H_R.

Table 1. Values of a_H, a_v, b_H and b_v (H horizontal polarisation, V · vertical polarisation)

Frequency GHz	a_H	a_v	b_H	b_v
1	0000387	00000352	912	880
2	000154	000138	963	923
4	.000650	000591	1 121	1 075
6	00175	.00155	1.308	1 265
7	00301	00265	1.332	1 312
8	00454	.00395	1 327	1.310
10	0101	00887	1.276	1.264
15	0367	0335	1 154	1 128
20	.0751	0691	1 099	1.065
25	124	113	1 061	1 030
30	187	167	1.021	1 000
35	.263	233	979	963
40	350	310	939	929
45	442	.393	903	897
50	536	479	873	868
60	707	642	826	824
70	851	784	793	.793
80	.975	906	.769	.769
90	1.06	999	753	754
100	1 12	1 06	743	744
120	1.18	1 13	731	.732
150	1.31	1 27	710	.711
200	1 45	1 42	689	690
300	1 36	1 35	688	689
400	1.32	1.31	683	684

The CCIR method of calculation of total attenuation along the slant path is given by [9, 10].

$$A_R = \alpha \, . \, L_e ,$$

where A_R is the attenuation exceeded for P% of time, α the specific attenuation and L_e the effective path length given by

$$L_e = r_p \, . \, L_S .$$

with r_p, the reduction factor is given by

$$r_p = \frac{90}{90 + C_p \cdot L_G}$$

and

$$L_S = \frac{H_R}{\sin\theta}.$$

Here, H_R is the rain height above the station elevation and θ is the elevation angle. The value C_p as given in the CCIR. [10] are 9, 4, 0.5 and 0 respectively for rains occurring for 0.001%, 0.01%, 0.1% and 1% of time. The parameter L_G is the horizontal projection of slant path.

Using the values of the measured rain rate data given in Table 1, rain height in relation to 0° C isotherm height and the various equations given above, the specific and one way total attenuation are estimated and the results obtained at 0.001% over Delhi are presented in Figure 5.

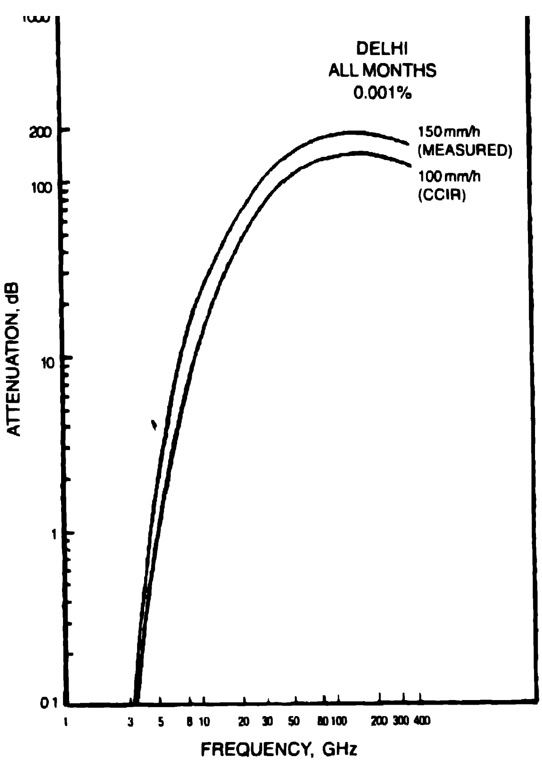

Figure 5. One way total attenuation due to rain over earth space path

8. Rain attenuation over terrestrial path

The relationship between attenuation, α, (dB/km) and rain rate, R (mm/h) for practical application is approximated by the power law [6] and is given in the previous section. The rain height is needed for earth space path while L_{eff} is required for terrestrial path. The effective path length L_{eff} is obtained by multiplying the actual path length L of the link by a reduction factor *r*. An estimate of this factor is given by

$$r = \frac{\quad}{1 + 0.045\,L}.$$

The estimation of the path attenuation is given by

$$A = \alpha_R \cdot L_{eff} = \alpha_R \cdot L \cdot r \ .$$

The results on attenuation for a terrestrial path located over Delhi is presented in Figure 6.

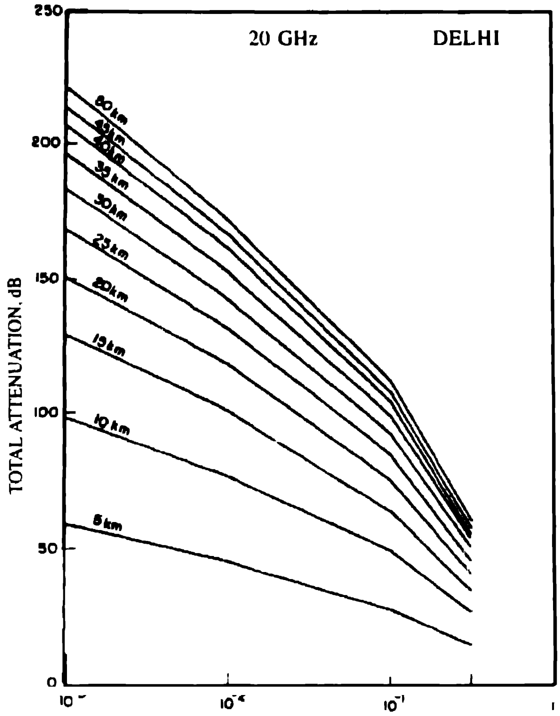

Figure 6. Total attenuation due to rain over terrestrial path.

9. Attenuation due to water vapour

The major atmospheric gases such as water vapour and oxygen need to be considered in the effective estimation performance of earth space communication links. In clear air, water vapour and oxygen absorption cause frequency dependent signal attenuation, propagation delay, ray bending and medium noise. The ultra short radiowave with resonant lines at 22.234 GHz, 183.3 GHz and 325.152 GHz are absorbed by water vapour which is the most important gaseous constituent of the lower atmosphere. The liquid water pressing in the atmosphere has strong absorbing effects on ultra short radiowaves due to the heavy displacement current. The attenuation due to oxygen molecule, is almost constant but it is not the case with water vapour whose concentration varies from place to place and from day to day since the saturation water vapour pressure is a very strong function of temperature. The saturation water vapour pressures are 6.1, 12.2, 17, 23.3 42.2 and 73.7 mbar at 0, 10, 15, 20, 30 and 40°C respectively.

In the gaseous atmosphere, at radio frequencies, scattering is not significant, so that emphasis has been laid to estimate the attenuation due to absorption. The total gaseous absorption, A_a (in dB), in the atmosphere over a path length r_o (in km) is given by [10]

$$A_a = \int_0^{r_o} \gamma_a(r) \, . \, dr \, ,$$

where

$$\gamma_a(r) = \gamma_o(r) + \gamma_\omega(r)$$

and γ_a is the specific attenuation in dB/km, γ_o and γ_ω are the oxygen and water vapour concentrations respectively.

The technique is based on an approximation on the use of Van Vleck-Weisskoff line with coefficients adjusted to fit the computer calculations. This led to the following formula

$$\gamma_\omega = \left[0.067 + \frac{2.4}{(f-22.3)^2 + 6.6} + \frac{7.33}{(f-183.5)^2 + 5} + \frac{4.4}{(f-323.8)^2 + 10} \right] \cdot f^2 \rho \cdot 10^{-4} \, .$$

where f is the frequency ρ is the water vapour density expressed in g/m$_3$. The above equation is valid upto 350 GHz.

The total attenuation over earth space path is obtained by integrating the above equation through the atmosphere. The troposphere plays an important role in slant path communication

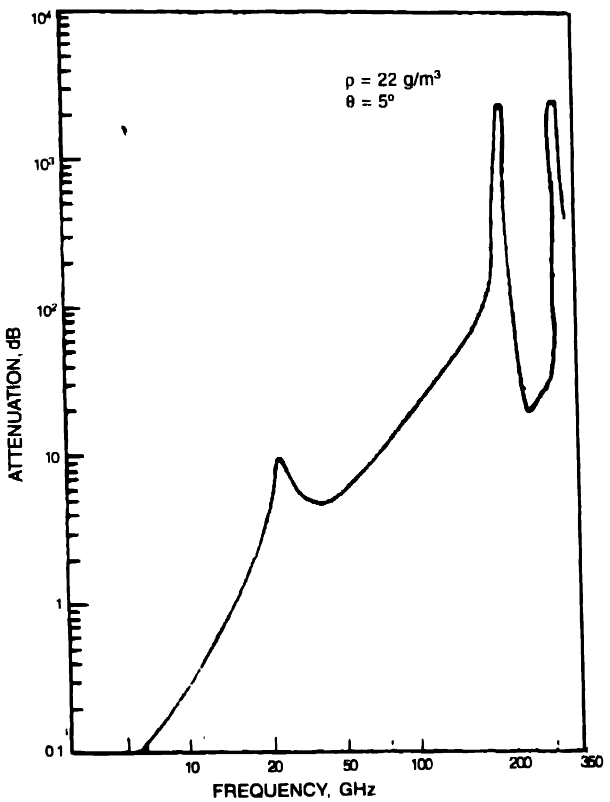

Figure 7. Attenuation due to water vapour over earth space path.

when the angle of elevation (θ) is less than 10^o. The concept of equivalent path is introduced for the real length of the atmospheric path and leads to the following relation

$$A = \frac{4\gamma_\omega}{\sqrt{(\sin^2\theta + 4 / R + \sin\theta)}},$$

where R is the effective earth's radius and A is the total path attenuation.

Based on the water vapour concentration (ρ) and observations, attenuation is estimated for different frequencies between 5 GHz and 350 GHz in different elevation angle (θ). A typical plot between attenuation and frequency for $\theta \sim 5^\circ$ and $\rho = 22$ gm/m^3 is presented in Figure 7. The attenuation due to water vapour concentration at ~ 22 GHz, 183 GHz and 325 GHz, which are the resonant frequencies for water vapour is of high order. Even at a frequency of ~ 30 GHz, which is considered to be the window region, the attenuation is considerable and is of the order of ~ 15 dB at 20 gm/m^3 water vapour concentration.

10. Conclusions

The most suitable methods for predicting transmission loss/field strength/attenuation under varied Indian meteorological conditions have been presented. Such methods can readily be used for estimation performance of both terrestrial and earth space communications links in VHF, UHF, microwave and millimetrewave bands located in any geographical regions in India.

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